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**MATERIAL - 4340 STEEL - STRESS CORROSION AND  
EFFECT OF BANDING - LITERATURE SURVEY**

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REPORT FGT-2957 Pt.I  
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MATERIALS - 4340 STEEL - STRESS CORROSION AND EFFECTS OF BANDING  
LITERATURE SURVEY

PART II Effects of Banding (To be published at a later date as an addendum to this report).

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## F O R E W O R D

This report was prepared by the GD/FW Materials Laboratory as a portion of a comprehensive program directed toward solution of the problem of occasional premature failures of high strength steel landing gears.

This report covers a literature survey of stress corrosion cracking of metal alloys since this phenomenon is suspected as a possible contributing factor in the overall problem.

The author would like to express his thanks to E. W. Turns and J. H. Halkias for substantial contributions to this report.

A report of a literature survey of the effects of banding on the properties of 4340 steel will be published at a later date as Part II of this report.

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LITERATURE SURVEY ON  
STRESS CORROSION OF 4340 AND 4335 STEEL

I N T R O D U C T I O N

PURPOSE AND OBJECTIVES OF THE SURVEY

Landing gears for high performance airplanes are of necessity fabricated from the highest strength steels available, yet compatible with present fabrication processes and techniques. Occasionally these high strength alloy steels fail prematurely. The purpose of this study was to perform a survey of readily available literature pertinent to stress corrosion cracking of metal alloys to determine if this phenomenon is a factor in premature landing gear failures. Specific objectives of the study were:

- (1) to gather information regarding stress corrosion of 4340 and 4335 steel;
- (2) to study the mechanism of stress corrosion cracking and ferret out established and reliable test methods for early detection of stress corrosion in 4340 and 4335 steel; and
- (3) to determine the state-of-the-art in methods for preventing stress corrosion in metals.





## NEED FOR INFORMATION

Recently, failures have occurred in landing gears which are made of cast and forged high heat treat 4340 steel. A typical analysis of 4340 low alloy steel is as follows:

Element	C	Mn	P	S
% by Weight	.40	.68	.020	.013
AMS-6115D (1)	.38/.43	.60/.85	.04 Max.	.04 Max.

Element	Si	Ni	Cr	Mo
% by Weight	.28	1.87	.74	.25
AMS-6115D (1)	.20/.35	1.65/2.00	.70/.90	.20/.30

Several theories have been advanced as to the cause of these premature failures. However, characteristics of the failure, e.g., direction of cracks in relation to stress, rapidity of failure, and location of failures in highly stressed areas, all lead to stress corrosion as the most logical explanation. For this reason, an urgent need developed for a comprehensive study of the available literature on the phenomena of stress corrosion in metals. Information assembled in one report should prove useful in establishing the role of stress corrosion cracking in the landing gear problem.



### SCOPE AND LIMITATIONS

Scope of this study was limited, as originally planned, to surveys of literature pertaining to 4340 and 4335 low alloy steel. An abundance of literature has been published on stress corrosion cracking. But as the survey progressed, it became apparent that very little has been published regarding these two steels, particularly in the high heat treat condition. The preponderance of published information on the subject concerns aluminum, magnesium and copper alloys as well as chromium and austenitic stainless steels. Thus the dearth of information was a limiting factor in this survey.

A further limiting factor is that much of the test work on these metals was done in liquid media or high concentrations of deleterious gases. Few of the references cited performed tests in natural outdoor environments and none correlated laboratory tests directly with actual service performance. Therefore, a direct correlation between information abstracted and compiled herein, can not be made with service performance.

### SOURCES OF INFORMATION

Literature surveyed in this study comprised books, metals handbooks, reports of Corrosion Symposiums, Department of Defense sponsored research reports and articles appearing in periodicals.



T H E P H E N O M E N O N O F S T R E S S C O R R O S I O N  
I N M E T A L S

DEFINITION OF TERMS

Evans defines stress-corrosion as cracking produced by tensional stress and corrosion acting together. The name should only be used where the damage exceeds that produced by stress and corrosion acting separately (2,p.660).

GENERAL DISCUSSION OF STRESS CORROSION

Berry, of Battelle's Defense Metals Information Center, conducted a survey (3) on stress-corrosion cracking and made the following observations: stress corrosion ---- "is characterized by a brittle-type fracture in an otherwise ductile material and the surface direction of the cracks is perpendicular to the direction of the stress load."

Other literature surveyed by Berry prompted him to record the following cautions:

1. Stress corrosion is not to be confused with increased general corrosive attack which sometimes is observed when a material is under stress; neither is it to be confused with other types of localized attack such as pitting, galvanic attack, intergranular corrosion, impingement, or cavitation.



2. Another type of failure often confused with stress-corrosion cracking is corrosion fatigue. When cracking results from materials being subjected to repeated flexing or bending in a corrosive environment, it is called a corrosion-fatigue failure. The cyclic stresses must involve tension at least part of the time. It should be emphasized that the stresses associated with stress-corrosion cracking are static rather than cyclic.

There are a number of general statements found in literature which further characterize stress corrosion. They are:

1. Stress corrosion cracking will occur in material under tensile stress but not under compressive stress.
2. Pure metals are not susceptible to stress corrosion cracking.
3. Slight changes in nickel composition of steels has a marked affect on stress corrosion susceptibility.

#### MECHANISM FOR STRESS-CORROSION IN 4340 AND 4335 STEEL

A specific theory for the mechanism of stress-corrosion in 4340 and 4335 was not found in the literature surveyed. Nevertheless, several references (3)(4) were found which described stress corrosion cracking tests conducted on 4340 and other



alloy steels. It is therefore safe to assume that these steels are susceptible to the phenomenon. Inference can be drawn from theories developed for other alloys with reasonable assurance that they will apply generally to the steels in question.

#### Conflict of Data

Much of the available experimental data on stress corrosion appears to be conflicting. The complexity of the problem and variables in test methods from one laboratory to another make such conflicts inevitable. However, Edeleanu (5) in his studies of the problem found that there is reasonably good agreement about the following facts:

1. Stress corrosion cracking is apparently a brittle type failure, (e.i. there is little plastic deformation) which can occur in highly ductile materials.
2. The rate of cracking is very low by brittle fracture standards but can be very high by normal chemical attack standards.
3. The cracking can be either inter-or transcrystalline, depending on the alloy. The intercrystalline cracking is, in many cases, associated with some stage of precipitation reaction, thus it is heat-treatment dependent. The transcrystalline cracking generally



occurs in the more highly alloyed material, such as the brasses, austenitic steels, and copper-gold alloys, and it is not normally very sensitive to heat treatment.

4. The chemical conditions which lead to cracking are highly specific and peculiar to the alloy system.

As the name of the phenomenon connotes, both factors — stress and corrosive conditions — must be present to cause a material to fail and be attributed to stress corrosion cracking. Investigators differ on the interdependency of the two factors as well as the role of each factor independently. The greatest difference of opinion exists on the role of corrosion. Some investigators emphasize the electrochemical phase while others minimize this phase and are proponents of the mechanical or two-stage process.

#### Electrochemical Theories

E.H. Dix, Jr., a proponent of the electrochemical theory, states in a comment on Edoleanu's paper (5,p.95) that he has shown by Cinematography that the progress of stress corrosion cracking can be stopped and started at will by the application of an external potential, where the highly stressed specimen is the cathode. His reasoning follows then that the chemical aspects of the phenomenon are of greater importance than the

mechanical aspects.

Evans (2,p.689) postulates that hydrogen can be involved in stress corrosion. His theory is that atomic hydrogen ( $H^{\circ}$ ) formed in the corrosion process may diffuse into cavities which lie ahead of the advancing crack and on combining to form molecular ( $H_2$ ), develop pressure in the cavity and cooperate with the applied tensile force — already intensified by geometrical considerations at the tip of the crack — to accelerate the advance of the crack.

Phelps and Loginow (4,pp.330t-331t), after demonstrating conclusively that very high strength steel can be susceptible to stress corrosion cracking, theorized on two possible mechanisms for this type of failure: Mechanisms described are:

1. Localized corrosion along a continuous active path through the steel, which would indicate that the anodic reaction on the metal surface is the dominate reaction.
2. General corrosion accompanied by hydrogen formation and subsequent "hydrogen embrittlement" type failure. This mechanism would indicate that the cathodic reaction on the metal surface is the dominant reaction.

Tests made by these researchers using 12 MoV stainless specimens, tempered at 800°F and at a stress level of 75



percent of yield strength, show that failure time in an aerated solution of 3 percent sodium chloride at  $75^{\circ} \pm 3^{\circ}\text{F}$  can be varied by applied current density. The failure behavior indicates that with no current, with anodic polarization, or with cathodic polarization at low current densities, the observed cracking is caused by corrosion along an active path through the steel. At cathodic current densities higher than  $0.137 \text{ ma/in}^2$ , hydrogen embrittlement is the probable cause of the cracking. Figure 1 taken from the work cited shows failure time of the specimens in minutes vs current density.

Undoubtedly, Edeleanu, a proponent of the "two-stage" process, would disagree with the "corrosion along an active path" theory. He states that he can not conceive of a chemical reaction proceeding at a rate rapid enough to account for the short time of failure.

#### Mechanical or Two-Stage Theories

Nielson (6, p.123-24) in his work on the role of corrosion products in crack propagation advanced the theory that solid corrosion products, cathodically deposited within cracks in steel, exert a wedging action which develops lateral tensile forces. He feels that these wedging forces, combined with the residual and applied stresses present, are sufficient to "trigger" spontaneous crack propagation.





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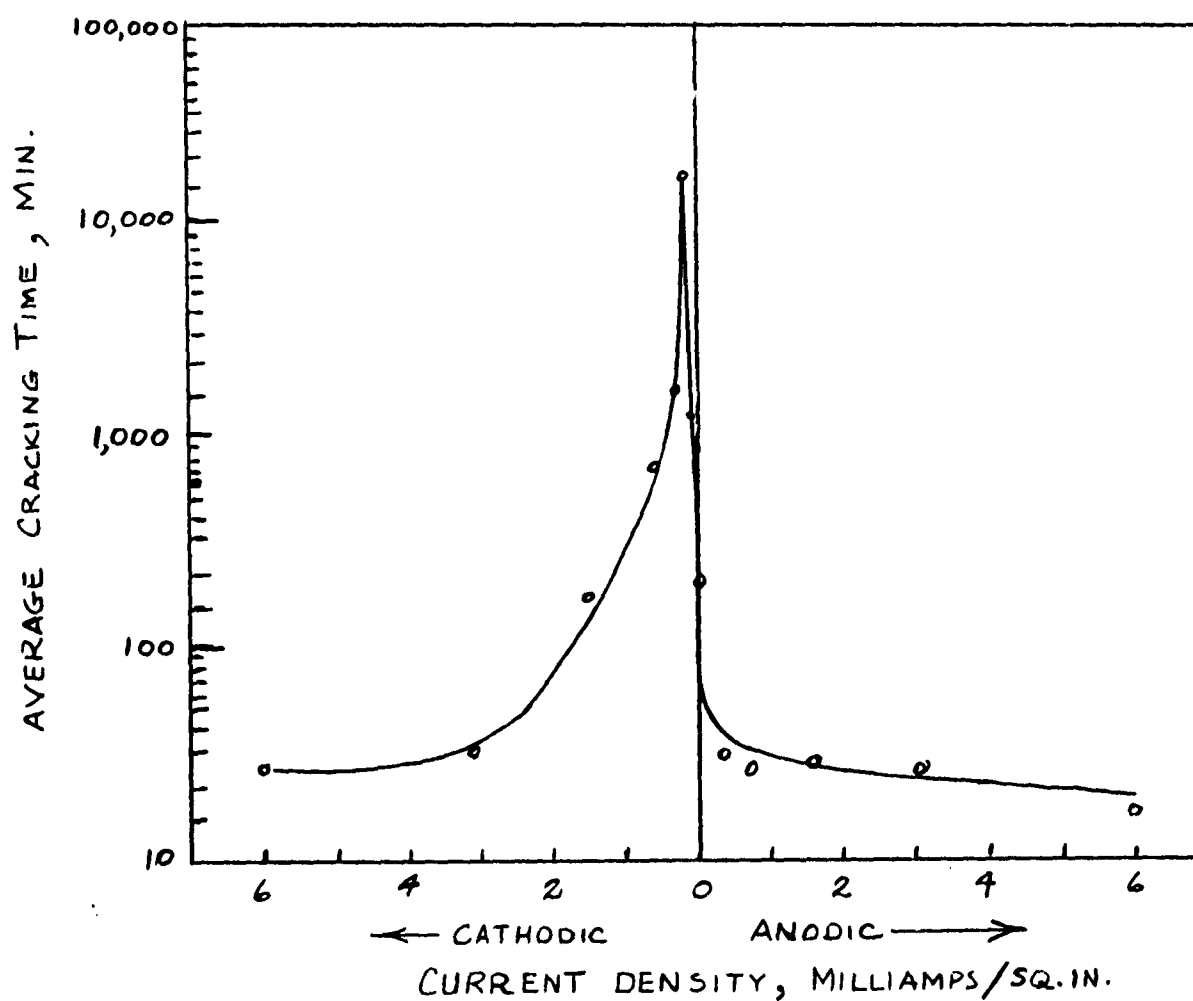


Figure 1 - Effect of applied current on cracking time, USS 12MoV stainless steel in aerated 3 percent NaCl solution (4).



Experimental studies are cited to support this theory. Nielson quotes work by Logan and Sherman (Welding Res. Supplement, Aug. 1956) in which they noted the presence of corrosion products immediately adjacent to stress corrosion cracks in Type 304 stainless steel. X-ray diffraction patterns indicated that the products were probably iron oxide ( $\text{Fe}_3\text{O}_4$  - ferrosofer-ric). Because the volume of this oxide is approximately 1.4 times that of the steel from which it is formed, Logan and Sherman state that, "any oxide of this type formed in the stress corrosion crack could exert a tensile force tending to open the crack further."

Edeleanu, in explaining the mechanism the "two-stage process," i.e., embrittlement by chemical environment followed by breakdown under stress, offers the following comments:  
(5,p.84)

1. Corrosion, for some reason still to be determined, can assist the initiation of cleavage.
2. Susceptible alloys are such that cleavage cracks, once initiated, can penetrate into sound material for an appreciable distance before halting.
3. The process is a repetitive one including a relatively slow chemical stage and a rapid mechanical stage.



Forty's work and theories (7,p.99) are in keeping with those of Edeleanu. He feels that the essential role of corrosion lies in the initiation of the cracks which results from corrosion embrittlement. The embrittlement zone must be large enough to allow a crack to start and then reach the critical velocity of propagation so that brittle fracture can continue when it passes into normal (ductile) metal.

#### EFFECT OF HEAT TREAT LEVELS ON SUSCEPTIBILITY OF 4340 AND 4335 STEELS TO STRESS CORROSION CRACKING

Investigators in the field generally agree that heat treat levels to which steels are subjected have a marked effect on their susceptibility to stress corrosion cracking, (2) and (4). Unfortunately, heat treat processes which improve resistance of steels to stress corrosion cracking also impart low tensile strength.

Specific information on the effect of tempering on the two steels in question was not found in this survey. However, information was found which should be applicable. Phelps and Loginow conducted tests on high strength steels which show correlation between tempering conditions and stress corrosion cracking (4). In their research, several steels were austenitized, then tempered at various temperatures and periods of time.



Specimens of these steels were stressed to 75% of yield strength during exposure to outdoor conditions at Kure Beach. Data on these specimens shown in Table I indicate that tempering conditions have a marked effect on stress corrosion cracking. It is also shown that tempering conditions which produce the highest strengths cause the most rapid stress corrosion cracking. All indications are that tempering conditions which impart high strength produce the greatest mechanical and electrochemical differences between the grains and grain-boundaries. This difference is conducive to stress corrosion cracking as described above.

Baldy found similar effects of tempering in tests of a C-Mn-Mo grade of steel commonly used for producing API Std. 5A, Grade N-80 tubular products (8). In a sulfide stress corrosion test, he found that specimens tempered at 1150°F had somewhat greater resistance to failure than those tempered at 1200°F. It was interesting to note that corrosion rate (metal removal) on the N-80 steel was independent of applied stress and prior thermal or mechanical history. This observation confirms those of other investigator's in the field that the corrosion involved in stress corrosion cracking is minute and often not readily apparent. Moreover, corrosion which influences stress corrosion cracking is different from that which is evidenced by actual metal removal.



TABLE I

## EFFECT OF TEMPERING TEMPERATURE ON STRESS CORROSION CRACKING

Steel	Heat Treat				Yield Strength psi x 10 <sup>-3</sup>	Tensile Strength psi x 10 <sup>-3</sup>	Failure Time at Kure Beach*
	Austenitizing or Conditioning		Tempering				
	Temp. °F.	Time Min.	Temp. °F.	Time hrs.			
<u>Alloy Steel</u>							
AISI 4340	1600	15	475	2	218	261	10
AISI 4130	1600	15	800	1/2	157	166	No failure after 175 days
-----							
<u>Martensitic Stainless Steel</u>							
Hot-work die Steel-Type B							
	1850	5	1000	4	229	327	4
Hot-work die Steel-Type B							
	1850	5	1100	4	203	244	3 failed in 250 days, 15 of 18 did not fail after 750 days

\* Stress Level - 75% Percent Yield Strength

OUTDOOR EXPOSURE VS. ACCELERATED LABORATORY  
TESTS FOR STRESS CORROSION

Phelps and Loginow conducted tests to show the effect of tempering temperature on the stress corrosion behavior of 12 MoV stainless and Airsteel X200 (4,p.330t). Duplicate sets of specimens were tested in the laboratory and at Kure Beach. Specimens were mounted in plastic holders to exert a stress level of 75% of yield strength on the specimens. Duration of the tests was 40 days in the laboratory in aerated 3% sodium chloride solution and one year at Kure Beach.

Results of this test are shown in Figures 2 and 3. A surprising difference between the laboratory and Kure Beach tests was observed with the untempered 12 MoV stainless and this steel tempered at 400, 500 and 600°F. Failure did not occur in 40 days in the laboratory test, whereas failure occurred in less than 10 days at Kure Beach. The explanation advanced by the authors for this anomaly is that in the laboratory, specimens are totally immersed in the conducting solution so that anodic activity on one portion of the specimens could influence the stress corrosion process in the center of the specimen where the stress is highest. In the atmospheric tests, it is believed that corrosion occurs under small water droplets so that a similar influence of one portion of the specimen on another portion would not be expected.

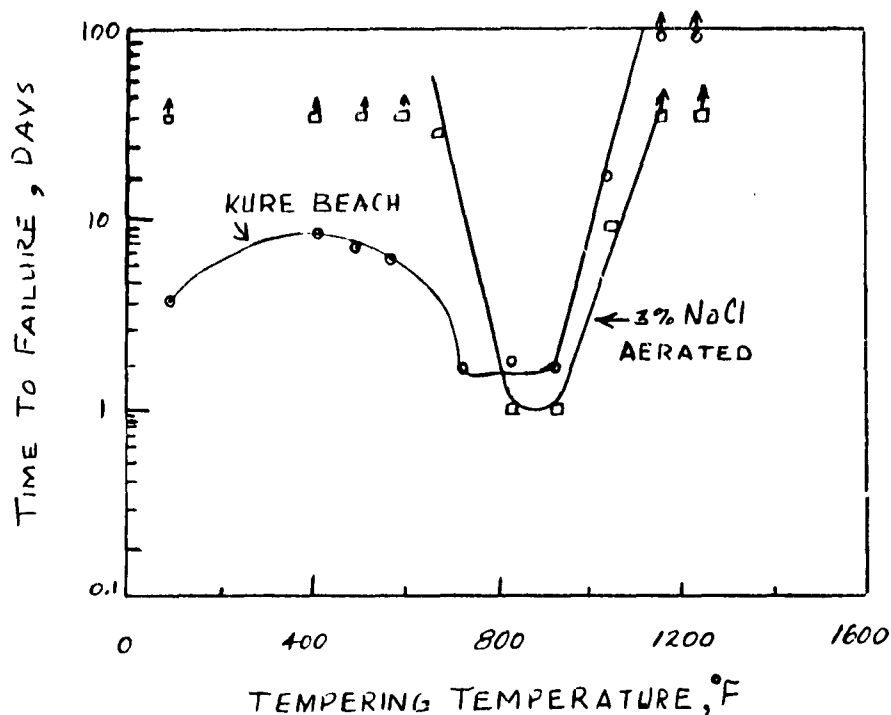


FIG. 2 Effect of tempering on stress corrosion of USS 12 MoV stainless steel (4).

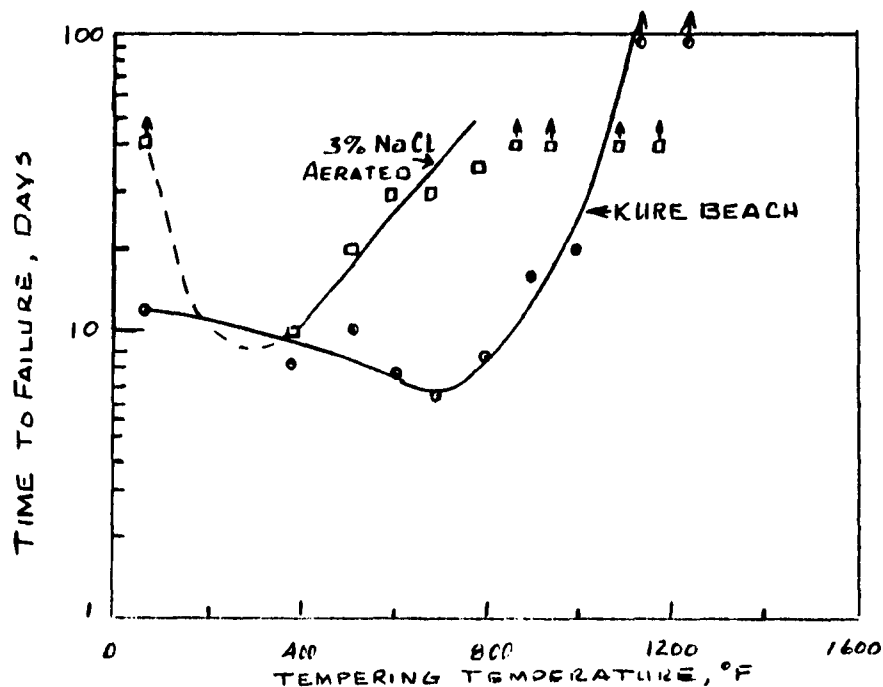


FIG. 3 Effect of tempering on stress corrosion of Airsteel X200 (4)



Although Phelps and Loginow did not conduct the above described tests with 4340 or 4335 steel, it is reasonable to predict that anomalies between laboratory and outdoor tests would occur with these steels the same as that which occurred with 12 MoV and Airsteel X200.

D E T E C T I O N   O F   S T R E S S   C O R R O S I O N  
S U S C E P T I B I L I T Y   I N   M E T A L S

In this literature survey, four methods for determining stress corrosion susceptibility in metals, other than actual exposure under stress and corrosive conditions, were found.

They are:

1. X-ray diffraction of metal surfaces for residual stresses.
2. Measurement of potential between grain bodies and grain boundaries.
3. Etching the metals surfaces, leaving stress cracks showing in relief.
4. Dissection of parts, with dimension measurements made before and after.

All four methods are designed for use in the laboratory. The first is the only nondestructive method and the only one which might be used in the field. A discussion of these four methods is as follows:





## X-RAY DIFFRACTION

X-ray spectrometers have been used extensively to study stresses in metals. Isenburger lists 240 references on X-ray stress analysis (9).

Norton of Massachusetts Institute of Technology and Rosenthal of University of California have presented several papers describing X-ray methods for stress analysis (10)(11)(12).

Norton and Rosenthal indicated that with proper techniques, X-ray diffraction can be used to determine residual stresses in metals caused by local plastic deformation, intense local heating, overstressing, surface treatment, and also the relief of residual stress by overstressing and heat treatment (11). Moreover, their work indicates that X-ray methods can be used to measure stresses in layers and recesses, and determination of true stress at a given depth below the surface as a function of apparent stress measured at successive levels above this depth (12).

Maloof and Erard used X-ray diffraction techniques to determine Poisson's Ratio in different crystallographic directions in a FS-8742 steel (13).

Miller, Mantel and Coleman of General Motors Technical Center undertook an investigation to determine the degree of



accuracy obtainable with X-ray diffraction in measurement of applied mechanical stress on strain and residual or internal stress in hardened steel (14). Tests indicated that X-ray diffraction (Christenson and Rowland Technique) measurement agree with electric resistance strain gages within  $\pm 5000$  psi. Their conclusions were: (1) that residual stresses can now be measured in hardened steel to an accuracy comparable to mechanical methods; and (2) in applications where surface values of residual stress are sought, the X-ray method has distinct advantages over mechanical methods. Christenson and Rowland of Timken Roller Bearing conducted similar studies of X-ray and SR-4 strain gage measurements of elastic strain, using hardened rings of SAE 4260 steel (15). Conclusions reached were to the effect that stress-strain measurements determined by X-ray methods compare with SR-4 strain gages within  $\pm 3000$  to  $4000$  psi. These conclusions correspond closely with those of Miller, et al., at General Motors.

#### MEASUREMENT OF POTENTIAL BETWEEN GRAIN BODIES AND GRAIN BOUNDARIES

Dix, Mears and Brown are strong proponents of the electrochemical theory of stress-corrosion. Their theory is that at the out-set of the stress-corrosion phenomenon, a potential difference between the grain boundaries and grain interiors is necessary. The existance of such a difference has been



skillfully demonstrated by Dix, et al. (16). Their method was to cut two identical specimens from a coarse-grained sheet; on one, all the grain boundaries are protected with an insulating, impervious coating, so that, on immersion in a liquid, only the grain boundaries are exposed, while on the other the bodies are coated but a zone about 1 mm wide left along the grain-boundaries. The two specimens were then immersed in an electrolyte and the potential between them measured. The grain boundary network is definitely anodic to the grain interiors.

The fact that the grain boundary coating is 1 mm makes little difference for the following reasons:

1. Local anodes on the cathodic area and local cathodes on the anodic area are insignificant in respect to potential between grain bodies and grain boundaries.
2. The exact potential between boundary and body in any event would be difficult to measure because it is different when first caused to occur by immersion but later becomes the same.

Later, Dix, et al., demonstrated by the above described technique the effect of duration of aging at 375°F on the electrode potentials of grain and grain boundaries (Fig. 4) of a high-purity aluminum-copper alloy containing 4.1% Cu.

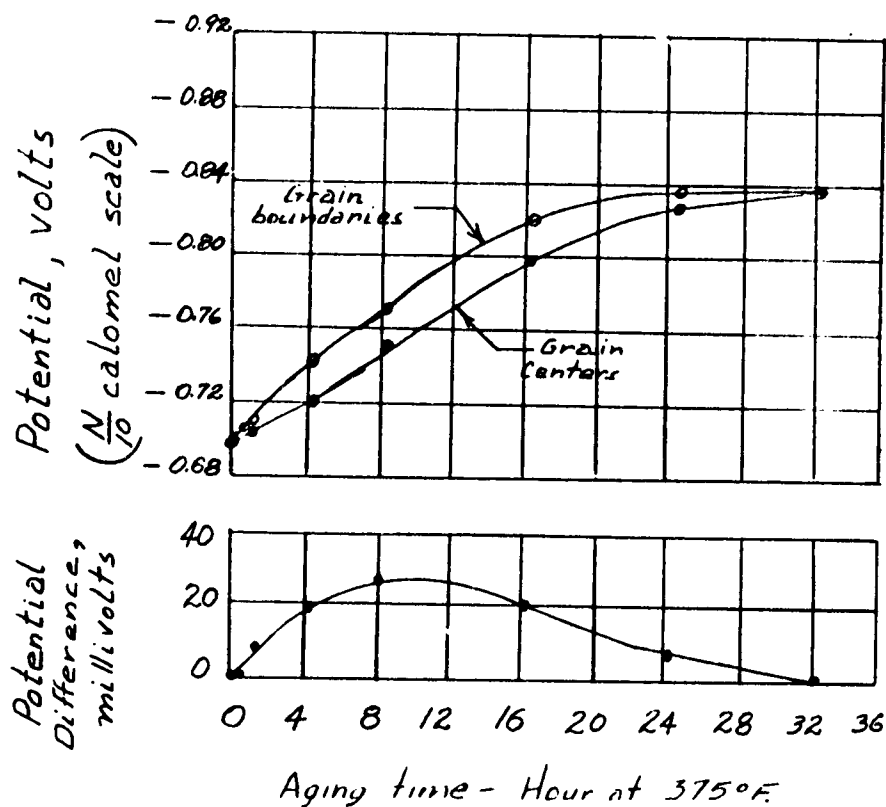


FIG 4 Effect of duration of aging at 375°F. on the electrode potential at grains and grain boundaries of a high-purity aluminum-copper alloy containing 4.10% Cu (16)



Artificial aging at temperatures in the vicinity of 375°F produces precipitation from the aluminum copper solid solution and a subsequent increase in the electrode potential of the alloy. Precipitation occurs more rapidly at the grain boundaries than within the grains, therefore, the boundaries become anodic to the grain centers. The maximum difference in potential between the grain boundaries and grain centers occur after aging 8-9 hours. Beyond this period, precipitation within the grain centers begin to catch up with that at the grain boundaries and after the alloy has been heated for 32 hours, virtual completion has occurred. Potential drops to almost zero. The alloy reaches its most susceptible stage for stress corrosion when precipitates along the grain boundaries form a complete or almost complete continuous film over the grain boundaries.

#### ETCHING THE METAL SURFACES, LEAVING STRESS CRACKS IN RELIEF

Neilson found that residual stresses developed in austenitic stainless steels due to quenching can be studied by the following method. The steel is first boiled several days in 42%  $MgCl_2$ . It is then etched in a 5% (by volume) solution of bromine in anhydrous methanol for an hour or so, then carefully washed free of bromine by successive transfers through several dishes containing methanol alone. Examination



of the etched surface reveals that cracks contain an inert corrosion product which remains intact and in relief to the etched surface. Prior to etching, these products usually can not be observed because the fine, hair-like nature of the cracks, and because the corrosion products themselves are film-like, being essentially two-dimensional (6).

The crack pattern in specimens treated as described above is quite discernible. Such a procedure appears to be a convenient method for studying residual stresses in other steels.

#### DISSECTION OF PARTS, WITH DIMENSION MEASUREMENTS MADE BEFORE AND AFTER

Rosenthal and Mazia studied the residual stresses in cartridge cases by saw-cutting the case to relieve circumferential stresses. Dimension measurements of the cases were made before and after cutting. Surface tensile and inter surface compression forces were then calculated based on changes in dimensions (17). Of course if the shell cases contained no residual stresses, distortion did not occur in the cases after sawing.



## METHODS FOR PREVENTING STRESS CORROSION IN METAL ALLOYS

Varying degrees of success have been achieved in preventing or reducing stress corrosion cracking of metal alloys. Procedures used can be classified as (1) surfaces finishes, (2) heat treatments, (3) electrochemical, and (4) application of surface coatings. It should be noted that none of the procedures is a panacea for prevention of stress corrosion cracking of all metal alloys. Each metal alloy may require a custom developed process for specific environmental service conditions.

### SURFACE FINISHES

#### Shot-Peening

Evans quotes the work of R. N. Parkins and C. E. Pearson (Welding Research, 1949, 3,95r) regarding shot-peening as a surface treatment to prevent stress corrosion cracking (2). Shot-peening (bombardment with shot) or hammer-peening (beating with a round headed hammer) are surface treatments capable of replacing tensile by compressional stresses, and of closing up any fissures which would otherwise act as stress-raisers.

Parkins considers peening less reliable than annealing, although he states that its benefits may persist after the compressed layer has been removed by general corrosion; if



localized, peening may even start cracking, doubtless by providing stress-raisers. It is suggested by Evans that a systematic study of peening processes-varying shot-size and shot-velocity, etc. - should be made to establish a reliable procedure. Evans suggests a study such as that made by Gould (A. J. Gould and U. R. Evans, J. Iron and Steel Inst., 1948, 160, 164). Gould carried out corrosion fatigue tests on high-carbon steel bars which had been peened in several ways. Finely ground bars of the same steel were run in the test as controls. Dilute sulfuric acid and sea water were the corrosion media. All of the peened bars gave higher endurances than the finely ground finish, but differed considerably among themselves; at fairly high stress-range, the "best" peening procedure gave about ten times the life of the "worst." Favorable results were obtained with large shot at low pressure, or small shot at high pressure which indicates the need of a fairly thick layer of compressed material.

#### Nitriding

The process generally known as nitriding might have application in preventing or retarding stress corrosion cracking of metal alloys. Special steels containing elements possessing an affinity for nitrogen, such as chromium and molybdenum (sometimes aluminum or vanadium) acquire,





when heated in anhydrous ammonia at about 500°C., a rim of hard material in a state of internal compression. This process is known as nitriding and has sometimes been described as chemical peening.

The compression arises from the fact that the nitrides of these metals mentioned are very voluminous, and yet hard, so that the metallic matrix by which they are surrounded is left in a state of compression. Evans cites work of Inglis and Lake (Trans. Faraday Society, 1931, 27, 803; 1932, 28, 715) in which steel which was nitrided showed a 12 fold improvement in corrosion fatigue over the same material not nitrided, (2, p. 728). Although this work with nitriding was in connection with corrosion fatigue, the process may have application in prevention of stress corrosion cracking.

#### HEAT TREATMENTS

The effects of heat treatments and annealing on stress corrosion cracking susceptibility of high strength steels is discussed earlier in this report under the heading, "Effect of Heat Treat Levels on Susceptibility of 4340 and 4335 Steels To Stress Corrosion Cracking."

Suffice it to say here that it is a well established fact that susceptibility to stress corrosion cracking in metal alloys varies with heat treatment, the same as do the mechanical properties. Unfortunately, in high strength



steels, the treatments which give the best mechanical properties are not the ones which provide the best corrosion resistance.

### ELECTROCHEMICAL

In the laboratory, stress corrosion cracking of metal alloys has been manipulated by anodic and cathodic polarization of small specimens in corrosive media such as 3% sodium chloride solution saturated with oxygen or air as discussed earlier in this report under "Electrochemical Theories." Bhatt and Phelps showed that polarization of 12 MoV stainless steel specimens in NaCl solutions at pH of 6.5 and 12.5 with low cathodic-current densities will markedly increase time to failure. Specimens were 0.57-inch wide and 0.020-inch thick, stressed to 75% of yield strength in plastic holders (18).

Evans cites experiments by Farmery in which stress corrosion cracks in aluminum magnesium alloy specimens were stopped abruptly half-way across the specimen by the application of a cathodic current (2, p. 691). Other researchers working in the field of stress corrosion cracking have reported similar findings (19).

Although electrochemical protection of aircraft landing gears is not applicable in the sense described above,



an understanding of the process is advantageous in selection of surface coatings.

### SURFACE COATINGS

Phelps and Loginow conducted experiments with 12 MoV stainless steel and hot-work die steel, Type A to determine the effect of coatings on their susceptibility to stress corrosion cracking (4). Specimens with the various coatings were stressed to 75% of their ultimate yield strength and exposed along with uncoated controls at both Kure Beach and at Monroeville, Pa., (an industrial atmosphere). After 420 days exposure the following coatings were best at both exposure locations: (1) aluminum applied by metallizing, followed by dip coating with hydrolized ethyl silicate; (2) Nickel-cadmium applied in accordance with AMS-2416, followed by diffusion at 630°F for one hour; and zinc-dust dibutyl titanate, air dried. These three coatings are anodic to both of the steels. Those coatings which were cathodic to the steels did not prevent cracking except electroplated nickel on 12 MoV. This coating was cathodic to the 12 MoV yet it delayed stress corrosion of the steel at both exposure locations. It should be noted that in this work, coating thicknesses varied considerably and individual results on some of the coatings tested varied widely.



For example, some identical specimens coated with aluminum-pigmented silicone paint failed after 7 days exposure while others had not failed after 420 days.

A further caution in the selection of coatings to prevent stress corrosion cracking is that some inhibitors of general corrosion attack have been found in some instances to accelerate stress corrosion cracking. Dix and Brown found this to be the case on some aluminum alloys (20).

#### C O N C L U S I O N S

1. High strength alloy steels, such as 4340 and 4335 are susceptible to stress corrosion cracking.
2. It is generally agreed by authorities on the subject that the underlying cause of stress corrosion cracking is the marked electrochemical difference in grain bodies. and grain boundaries. There is conflicting opinions on how corrosion and stress (tensile) cause the phenomenon to occur.
3. X-ray diffraction appears to be an excellent non-destructive test method for determining stress corrosion cracking susceptibility of metal alloys.



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4. Indications are that shot-peening followed by coatings (paints or platings) anodic to the substrate to be protected is an acceptable procedure for prolonging the time before stress corrosion cracking starts in a susceptible metal alloy.



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